Positioning Method for Agricultural Autonomous Vehicles with a Simple Laser Sensor (Part 1)

— Position initialization method for autonomous traveling by using least squares method —

Takehide INAHATA*1, Tomohiro TAKIGAWA*2, Masayuki KOIKE*2, Toshio KONAKA*3, Akira YODA*2

Abstract

A new positioning method for agricultural robots with a simple laser sensor was developed. At the initializing stage of autonomous traveling, the position and the direction of an autonomous vehicle at a standstill should be fixed as the x and y coordinates and the angle with respect to x coordinate on a field map. This paper deals with a positioning method for initializing, in which a simple laser sensor was used to measure direction angles of light reflectors set around a field. The position and the direction of the vehicle was calculated by the least squares method, which enabled us to estimate measurement accuracy, and give the covariance matrix of the obtained position and direction. Field experiments were carried out to verify the measurement method. The accuracy obtained by the method was within 4 cm in a 40 m40 m field. Application of the dilution of precision factor are also discussed.

[Keywords] autonomous traveling, laser switch, least squares method, initialization, dilution of precision

I Introduction

Japanese agriculture is facing many difficulties such as a decrease in farming population, the aging of farmers, delays in the expansion of operations and pressure to open the market. Under these severe circumstances, it is expected that agricultural robots will work as a supplementary labor force for agriculture to make Japanese farm products more competitive.

An autonomous traveling system is one of the basic functions required for agricultural robots. Such autonomous traveling systems can be classified into three categories. In the first, an autonomous agricultural vehicle controller measures its absolute position and then determines optimal steering to follow a predetermined course. The absolute position is usually expressed as the x and y coordinates on a field map. The second is a system in which the vehicle runs based on a relative position, i.e. the geometrical disposition between the vehicle and an object such as a plant row. A vision-guided vehicle is a typical example of the relative position traveling system. In the third, several autonomous vehicles co-operate with one another. This study deals with the first system.

The autonomous traveling controllers must have several functions such as path planning, positioning of the vehicle, and path following control11. Positioning is important to maintain
the accuracy of traveling. Many positioning systems have been developed for autonomous robots. Everett\textsuperscript{2} reviewed positioning techniques such as dead reckoning, tactile sensing, ranging, electromagnetic energy measurement, guide path detection and RF position-location system. For agricultural application, various positioning methods have been proposed. Dead reckoning is a simple method for determining the present position from the previous position and traveling distance or speed and direction measured with internal sensors over a given length of time. For example, Motohashi et. al.\textsuperscript{3,4} used fifth and sixth wheels as internal sensors and Ishida et. al.\textsuperscript{5} developed a system equipped with an ultrasonic Doppler speedometer and an fiber optic gyro. Though they have reported that dead reckoning is sufficiently accurate in short distances, trends to accumulate observation errors, thus for longer distance traveling an error correction with external reference is needed.

One of the most feasible methods presently available for agricultural use may be the Global Positioning System (GPS). The positioning accuracy of the advanced differential GPS, called "real time kinematic GPS", is within less than 2 cm. Successful results\textsuperscript{6,7} have been reported on an autonomous traveling system equipped with DGPS. However, the advanced DGPSs are presently too expensive for agricultural application, and have some problems in application. For example a GPS receiver installed in an autonomous vehicle must continuously get a correction signal from a fixed station. However in fields hidden by obstacles, such as woods or hilly land topography, the correction signal is interrupted frequently.

Positioning methods using external references have also been discussed. Triangulation ranging by a photoelectric sensor or a laser sensor is frequently applied method. Yukumoto et. al\textsuperscript{6,8} employed a photoelectric sensor for detection of light from reflectors and measured angles between reflectors. The position of the vehicle equipped with the photoelectric sensor was calculated by triangulation method. Simada et. al.\textsuperscript{9} reported performance of a system developed by Honda Co., which is basing on the same principle. Though their experimental results showed positioning accuracy of triangulation ranging by photo sensor was around 10cm in 50m $\times$ 50m fields, effect of inclination of the vehicle and error induced by running were remained for future study. The former problem comes from the fact that the light transmitted from the vehicle missed light reflectors when it is inclined. In triangulation survey, it is assumed that the vehicle is stopping, thus when vehicle is running, the latter problem will appear. Hence it can be said that no definite localization technique applicable to autonomous traveling vehicles, especially in mountainous areas, has been established yet.

In this study we will propose an improved triangulation system composed of inexpensive simple sensors for positioning: laser switch and dead reckoning sensors(i.e. tire rotation sensors and a fluxgate compass). In this system, to avoid problems stated above the following methods were used. The laser beam is oscillated vertically in order to catch light reflectors constantly. Sensor data fusion technique was employed for positioning during running.

Basic scheme of our positioning can be described as follows:

A. Static positioning (When the vehicle is stopping)

At the beginning of autonomous traveling, the position and the direction of the vehicle are usually not known. In most autonomous traveling systems, an operator provides the initial location, but the quality of such information is usually low.
Though some positioning methods, such as GPS, provide x and y coordinates directly, in many other methods the relationship between sensor outputs and the coordinates of a field map should be determined at the time of initiation. The problem comes from the fact that many sensors used for positioning usually don’t output absolute values, but changes from initial values. For example, the yaw angle of the vehicle measured by the gyro sensor is the angular change from the initial direction. Consequently if error is included the initial direction determined in the initializing stage, the error will occur continually. From this point of view, triangulation positioning has been developed. In addition, we can reset position estimation error in a certain range by stopping the vehicle and applying this method.

B. Dynamic positioning (When the vehicle is running)

As mentioned previously, when the vehicle running, the triangulation method doesn’t give correct position. Thus we used dead reckoning in combination with laser sensor scanning. Dead reckoning is a simple and cheap way for positioning. This method gives an acceptably accurate position in short traveling distance, but the positioning error due to observation error grows rapidly as traveling distance increases, because this method integrates observed values. Therefore information given by the laser sensor scanning was used as a way of correction by applying sensor data fusion technique. In this method, when one directional angle of light reflector is measured, the correction can be done and hence the effect of running can be omitted.

This paper deals with the position initialization method and the positioning method during travel will be reported in Part 2.

II Experimental positioning system

A radio-controlled tractor was modified for computer control. The brakes, clutch, gear shift lever and the steering of the tractor are activated by hydraulic power according to signals from the computer.

A schematic diagram of the sensor system implemented in the experimental vehicle is shown in Fig.1. The two main sensory systems for positioning are a laser switch system and a dead reckoning system. The dead reckoning system consists of tire rotation sensors and a fluxgate compass. In this study, two optical encoders were used to measure the rotational speed of rear wheels. A rubber wheel was attached on the encoder shaft, and the encoder was installed on the tractor so that its rubber wheel come into contact with the inner carcass of the tire. A spring was used to force the rubber wheel onto the carcass surface, and sandpaper was pasted on the inner surface of tire carcass to prevent slipping.

The laser switch system is composed of a laser switch and a scanning apparatus. The laser switch has two simple functions of transmitting a near infrared laser beam and detecting the reflected light by a photodiode. In this study corner cube prisms of 30mm in diameter were used. In the performance test in a field, it was confirmed that the laser switch could detect the light reflector at distance of 250m. The switch is rotated around the verti-
cal axis for scanning light reflectors by a DC powered motor equipped with reduction gears and an optical encoder for direction measurement as shown in Fig. 2. The resolution of the directional angle is 0.0036 degree per pulse. Horizontal scanning speed can be varied by program. In this study it was set at 11.25.

Since the laser beam moves up and down as the vehicle rolls and pitches, the beam frequently misses the reflectors when the vehicle runs on a rough surface. To avoid this problem, the laser beam of the switch scans vertically by using a rotating tetragonal mirror as shown in Fig. 2. As the rotation speed of the tetragon mirror is 7000 rpm, scanning frequency is 0.00214.

III Position initialization for autonomous vehicles

1. Positioning based on the triangulation method

In this chapter, we will discuss the application of the least squares method for positioning. This method is applicable when there are at least three light reflectors, and gives a covariance matrix of estimated position, from which we can evaluate the accuracy of positioning.

Figure 3 shows the geometrical relationship of positioning by the laser switch, from which the following measurement equation can be derived.

\[ f(x, y, \theta_y) = (Y_L - y) \cos(\alpha + \theta_y) - (X_L - x) \sin(\alpha + \theta_y) \] (1)

\[ f = a_x dx + a_y dy + a_\theta d \theta_y \] (2)

where \((x, y)\) are the coordinates of the vehicle, \((X_L, Y_L)\) are the coordinates of the light reflector, \(\alpha\) is the measured angle of the reflector and \(\theta_y\) is the heading angle of the vehicle. Theoretically, the value of the above equation is zero; however, in actual measurements the value does not equal to zero but has a certain value \(f\), because of error inherent in measurement. We can assume that observation errors can be expressed by a normal distribution. When observation is repeated \(n\) times from fixed position, the least squares method can be applied to find out \((x, y, \theta_y)\) which make residual error after adjustment minimum as follows\(^{10,11}\).

First, the equation must be linearized around a temporary position given by an operator, because the observation equation (1) is nonlinear. The linearization gives:

\[ a_x = \frac{\partial f}{\partial x} = \sin(\alpha + \theta_y) \] (3)

\[ a_y = \frac{\partial f}{\partial y} = -\cos(\alpha + \theta_y) \] (4)

\[ a_\theta = \frac{\partial f}{\partial \theta_y} = -(Y_L - y) \sin(\alpha + \theta_y) - (X_L - x) \cos(\alpha + \theta_y) \] (5)

If the position is adjusted in \(\Delta X = [\Delta x, \Delta y, \Delta \theta] \).
\[ \Delta \theta^T \], the residual matrix after the adjustment \( V \) will be given as:

\[
V = A \Delta X + W
\]

where

\[
A = \begin{pmatrix}
a_{x1} & a_{y1} & a_{\theta1} \\
a_{x2} & a_{y2} & a_{\theta2} \\
\vdots & \vdots & \vdots \\
a_{xn} & a_{yn} & a_{\theta n}
\end{pmatrix}, \quad W = \begin{pmatrix}
f_1 \\
f_2 \\
f_3 \\
f_n
\end{pmatrix}
\]

Then the matrix \( \Delta X \) which makes \( V^TPV \) minimum is the least squares estimate of the adjustment. \( P \) is the weight matrix defined as:

\[
P = \sigma_0^2M^{-1}, \quad M = \begin{pmatrix}
\sigma_1^2 & 0 & 0 & 0 \\
0 & \sigma_2^2 & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \sigma_n^2
\end{pmatrix}
\]

where the matrix \( M \) is the covariance matrix of the observation, \( \sigma_0^2 \) is the scale factor and the superscript \(^{-1} \) indicates the inverse matrix.

A necessary condition for the minimization is that the partial derivatives of equation (6) must be zero. This condition yields:

\[
\Delta \hat{X} = -(A^TPA)^{-1}A^PW
\]

Clearly the new position can be calculated as:

\[
\hat{X}_{\text{new}} = \hat{X}_{\text{old}} + \Delta \hat{X}
\]

Because the observation equation is nonlinear, the solution must be iterated.

Next we can calculate the covariance matrix of the expected position after the iteration. Confidence regions of each estimations can be calculated from this matrix. In addition such matrix is requisite for Kalman filter correction to be reported in the part two. From the law of variance-covariance propagation, the cofactor matrix becomes:

\[
Q_X = (A^TPA)^{-1} = \begin{pmatrix}
Q_{x1,1} & Q_{x1,2} & Q_{x1,3} \\
Q_{x2,1} & Q_{x2,2} & Q_{x2,3} \\
Q_{x3,1} & Q_{x3,2} & Q_{x3,3}
\end{pmatrix}
\]

The variance, called a posteriori variance, is computed from:

\[
\hat{\sigma}^2 = \frac{V^TPV}{n-m}
\]

where \( m \) is the number of adjusted variables, in this case, 3. The covariance matrix \( \Sigma \) can be given by:

\[
\Sigma = \begin{pmatrix}
\sigma_x^2 & \sigma_{xy} & \sigma_{x\theta} \\
\sigma_{yx} & \sigma_y^2 & \sigma_{y\theta} \\
\sigma_{\theta x} & \sigma_{\theta y} & \sigma_{\theta}^2
\end{pmatrix} = \sigma^2Q_X
\]

Confidence region can be calculated basing on the fact that following values belong to \( \chi^2 \) distribution.

\[
(\hat{X} - X) \Sigma^{-1}(\hat{X} - X) < \chi^2
\]

The dilution precision factor (DOP) is an index to describe the effect of the geometric configuration of signal sources on the accuracy of positioning, and used to express the effect of the geometric distribution of satellites on GPS accuracy. Equation (13) shows variances after adjustment is given by multiplying a posteriori variance of unit weight (\( \hat{\sigma} \)) and elements of matrix \( Q_X \). Here \( \hat{\sigma} \) indicates variance of observation and \( Q_X \) shows effect of geometrical configuration of light reflectors. Generally the diagonal elements of \( Q_X \) are used to indicate DOP. In this case, \( Q_{x1,1} = DOP_x \) is degree of variance in x-direction, \( Q_{x2,2} = DOP_y \) is in y-direction and \( Q_{x3,3} = DOP_{\theta} \) is in \( \theta \). Thus it may be possible to determine the arrangement of light reflectors by repeating calculations of DOP factors until diagonal elements of the matrix are in an acceptable range.

2. Effect of inclination

The positioning method derived in the previous section does not take the effect of vehicle inclination into account. The pitch and roll of a vehicle cause calculation error. Figure 4 shows the distribution of the error when both of the rolling and pitching angles of a vehicle are 3 degrees. It can be seen that rolling and pitch produce a calculation error of up to 6cm. When a vehicle staying at \((x, y)\) pitches and rolls without vertical movement, it produces an effect that is equivalent to moving the light reflector from \((X_L, Y_L)\) to \((X_L', Y_L')\):
where $\theta_P$ and $\theta_R$ are the pitching angle and the rolling angle respectively. Terms including $Z_l-z$ are less than 5mm when the inclination angles are less than 5 degrees, hence negligible. A new observation equation is given:

$$X'_l = (X_l - x) \cos \theta_y \cos \theta_P - \sin \theta_y \sin \theta_P \sin \theta_R + (Y_l - y) \sin \theta_y \sin \theta_P \sin \theta_R + (Z_l - z) \sin \theta_P \cos \theta_R$$

$$Y'_l = -(X_l - x) \sin \theta_y \cos \theta_P + (Y_l - y) \cos \theta_y \cos \theta_R - (Z_l - z) \sin \theta_R$$

where $\theta_P$ and $\theta_R$ are the pitching angle and the rolling angle respectively.

A new observation equation is given:

$$f(x, y, \theta_y) = Y'_l \cos \alpha - X'_l \sin \alpha$$

As this observation equation includes effects of rolling and pitching of the vehicle, the accuracy of estimation may improve.

### IV Positioning experiment

Positioning experiments were conducted in a square field of 40m x 40m. The locations of light reflectors and positioning points were surveyed by the surveying total station (Topcon AP-L1). Figure 5 shows the locations of light reflectors by white and black circles, and positioning points by triangles. In the first experiment (Experiment 1), all light reflectors were used, then to check the effect of light reflector location on positioning accuracy, we removed the light reflectors denoted by black circles in Fig. 5 and repeated positioning experiment (Experiment 2). To eliminate the effect of inclination and to set the sensor accurately, a tripod for surveying was used. Scanning of light reflectors was done 10 times.

To clarify repeatability of measurements and effect of distance, variation of measured angles was calculated and plotted in Fig. 6. Here we can see that in the range of this experiment, standard deviations of measured angles were less than 0.15 degree. Though there is a weak
positive correlation between the standard deviation and the measuring distance, the standard deviation is a nearly constant value of 0.1 degree in the range of distance.

Table 1 is the positioning accuracy obtained in the experiment 1. Time required to calculate position from 54 measured angles was 4.8 ms with a personal computer equipped with 80486DX4 100MHz processor, however measurement took about 32 seconds for 1 scanning of 360 degree. Almost all errors in the x and y directions were less than 2 cm and the biggest offset was 4 cm. Directional errors were less than 0.2 degree. These results suggests that

Table 1 Positioning error obtained in the experiment

<table>
<thead>
<tr>
<th>Actual Values</th>
<th>Estimated Values</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>X[m] Y[m] θ [°]</td>
<td>X[m] Y[m] θ [°]</td>
<td>X[m] Y[m] θ [°]</td>
</tr>
<tr>
<td>5 5</td>
<td>66.68</td>
<td>5.02</td>
</tr>
<tr>
<td>10 5</td>
<td>74.05</td>
<td>10.03</td>
</tr>
<tr>
<td>15 5</td>
<td>81.87</td>
<td>15.01</td>
</tr>
<tr>
<td>20 5</td>
<td>90</td>
<td>20.02</td>
</tr>
<tr>
<td>5 10</td>
<td>63.44</td>
<td>5.02</td>
</tr>
<tr>
<td>10 10</td>
<td>71.57</td>
<td>9.99</td>
</tr>
<tr>
<td>15 10</td>
<td>80.54</td>
<td>14.98</td>
</tr>
<tr>
<td>20 10</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>5 15</td>
<td>59.04</td>
<td>5</td>
</tr>
<tr>
<td>10 15</td>
<td>68.2</td>
<td>9.99</td>
</tr>
<tr>
<td>15 15</td>
<td>78.69</td>
<td>14.96</td>
</tr>
<tr>
<td>20 15</td>
<td>90</td>
<td>19.99</td>
</tr>
<tr>
<td>5 20</td>
<td>53.13</td>
<td>4.99</td>
</tr>
<tr>
<td>10 20</td>
<td>63.34</td>
<td>10</td>
</tr>
<tr>
<td>15 20</td>
<td>75.96</td>
<td>14.99</td>
</tr>
<tr>
<td>20 20</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 2 Positioning error under worse configuration of light reflectors

<table>
<thead>
<tr>
<th>Actual Values</th>
<th>Estimated Values</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>X[m] Y[m] θ [°]</td>
<td>X[m] Y[m] θ [°]</td>
<td>X[m] Y[m] θ [°]</td>
</tr>
<tr>
<td>5 5</td>
<td>66.68</td>
<td>5.06</td>
</tr>
<tr>
<td>10 5</td>
<td>74.05</td>
<td>9.93</td>
</tr>
<tr>
<td>15 5</td>
<td>81.87</td>
<td>14.83</td>
</tr>
<tr>
<td>20 5</td>
<td>90</td>
<td>19.92</td>
</tr>
<tr>
<td>5 10</td>
<td>63.44</td>
<td>4.99</td>
</tr>
<tr>
<td>10 10</td>
<td>71.57</td>
<td>10</td>
</tr>
<tr>
<td>15 10</td>
<td>80.54</td>
<td>14.98</td>
</tr>
<tr>
<td>20 10</td>
<td>90</td>
<td>19.99</td>
</tr>
<tr>
<td>5 15</td>
<td>59.04</td>
<td>5.06</td>
</tr>
<tr>
<td>10 15</td>
<td>68.2</td>
<td>10.03</td>
</tr>
<tr>
<td>15 15</td>
<td>78.69</td>
<td>14.99</td>
</tr>
<tr>
<td>20 15</td>
<td>90</td>
<td>20.01</td>
</tr>
<tr>
<td>5 20</td>
<td>53.13</td>
<td>5.04</td>
</tr>
<tr>
<td>10 20</td>
<td>63.34</td>
<td>10.03</td>
</tr>
<tr>
<td>15 20</td>
<td>75.96</td>
<td>15</td>
</tr>
<tr>
<td>20 20</td>
<td>90</td>
<td>19.99</td>
</tr>
</tbody>
</table>

The results of the experiment 2 are listed in Table 2. Compared with the previous results, we can see that positioning accuracy was worse in this configuration. To check the effect of the DOP on the positioning accuracy, Figure 7 was plotted based on the experimental data obtained in these two experiments. In the figure, absolute error is defined as:

$$E_{abs} = \sqrt{E_x^2 + E_y^2}$$

where $E_{abs}$ is the absolute error and $E_x, E_y$ are errors in the X and Y directions, respectively. In the same manner, PDOP is defined as:

$$PDOP = \sqrt{DOP_x^2 + DOP_y^2}$$

When comparing absolute error obtained in two experiments, we can see absolute errors of the experiment 1, whose PDOPs are less that 0.9, are smaller than those in the experiment 2, whose PDOPs are from 1.4 to 22.6. However there is no clear correlation between the PDOP and the absolute error. Hence we cannot derive any conclusion on the effect of PDOP yet.
V Discussion and Conclusion

To develop an accurate position initialization method, we have constructed a positioning system by using a simple laser sensor, and investigated the application of the least squares method to the calculation of position. The developed method was tested through field experiments. The positioning accuracy in this method was less than 4cm and directional accuracy was within less than 0.2degree in a 40m x 40m field. It can thus be concluded that the method has acceptable accuracy for initialization in small fields. In addition, we can get accurate position and direction of an autonomous vehicle when it is stopping, allowing us to adjust the positioning error whenever we want. This aspect will be discussed in Part 2 of this study.

The utilization of the DOP factor was checked. The absolute error obtained in lower DOP configuration was smaller than that in higher DOP, however we could not confirm the effect of DOP on the accuracy of positioning clearly. It can be thought that errors included in settings of light reflectors and the laser sensor were too big to get clear relationship, consequently more precise experiments should be required to get conclusion.

Though a correction method for correcting inclination error has been proposed in this paper, verification has been left for a future study. Since the standard size of paddy fields in Japan is 30m x 100m, our method can be applied to small fields including paddy fields of the standard size. However, enlargement of field size is one of key factors which help to reduce production costs in Japanese agriculture. Thus a more intelligent system should be developed to apply our method to larger fields.

Acknowledgement

This research was supported in part by a grant from National Agriculture Research Center under the title of "Integrated study on the development of basic techniques for future agricultural mechanization". The authors would like to express thanks for this grant and the persons concerned. We also wish to thank Agricultural and Forestry Research Center of the University of Tsukuba for providing us research fields and Dr. Ronald J. Palmer of the University of Regina for his inspiring suggestions.

References


(Received : 4 June 1998 · Question time : 31 May 1999)
「研究論文」
レーザーセンサを用いた車両位置計測法の研究
（第1報）
稻畑健英*1、瀧川具弘*2、小池正之*2、小中俊雄*3、
余田 章*2

要旨

単純な機能を持つレーザーセンサを利用して位置決め方式を開発した。自律走行を開始するためには、まず、車両の位置と方向を車両に設定された図面上で座標値と角度として確定すること、つまり初期化操作が必要である。この論文では、場の周辺に設置した光反射標識の方向を単純なレーザーセンサで計測して初期化を行う方式を報告する。この方式では、車両の位置と方向を最小二乗法で計算した。最小二乗法により、計算された位置と方向の共分散行列も得られるので、計測の精度を推定できる。この方式の有効性を実験で検討した結果、40m角の場であれば5cm以下の精度で位置決めが可能であることがわかった。さらに、光反射標識の設置について、OP（Dilution of precision）の利用についても実験を通じて評価した。

＊1 学生会員、筑波大学農学研究科
＊2 会員、筑波大学農林工学系
＊3 会員、筑波大学名誉教授

コメント

センサだけのコストを考えると安価かもしれないが、精度よく位置決めするには光反射標識の位置が精度よく求めることが必要である。実用化を考えるとこれらのコストも考慮すべきで、結果的に高価なものになる可能性があるように思われる。したがって、位置推定法としては、本方式や生研機関のXNAVのように外部標識に頼る方式よりRTKDGPS（近い将来100万円位になる可能性がある）のような単独で位置推定を行う方式が有利であると考えられる。著者の見解を伺いたい。

【回答】

標識位置は測量により設置する必要がある。コストはそれほど高いかではないと思います。GPSについてはいろいろな考え方があります。本研究は自己完結したものです。GPSと関連づけて考えられる場合には将来の夢も含めて次のように考えます。RTKの可能性を指摘にされましたが、より広くみますと、この10年間で次世代の衛星（搬送波L5の追加）の打ち上げ、SA（Selective Availability）の廃止などが予定され、単独測位でも5mに近い精度が得られるとの予測があります。また、精度の低いRTKを内界センサとフュージョンして5cm程度の位置精度を得るとの報告もあります。このようなにしてみると、将来のGPSの利用ではなく、単独で精度の高いRTKだけでなく、内界、外界センサとのセンサデータフュージョンにより安価なGPSの精度を向上させる方法も考えられると思います。さらに、本論文で指摘したように、補正信号や衛星からの信号が途絶えること、GPSでは精度の高い位置計測に時間を要することなどのGPSの欠点も、外界センサと組み合わせれば回避できます。ですから、本研究の手法がGPSと共存することが十分可能と思います。今後、このような視点からも研究を継続させていく予定です。